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INVESTIGATION OF THE PLASMA BEHAVIOR IN AN AC ELECTRIC FIELD. PART 2

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INVESTIGATION OF THE PLASMA BEHAVIOR IN AN AC ELECTRIC FIELD. PART 2

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ABSTRACT: In this paper the results of an investigation of the behavior of a plasma in the presence of both an ac electric field and a magnetic field are presented. The relative change in the ac electric field in the discharge chamber with plasma was measured under different magnetic field intensities (0-1200 oe,) plasma densities (10^{8}-10^{10} cm^{-3}), gas pressures (10^{-1}-10^{-2} torr) and frequencies (1.5 X 10^{5} to 1.5 X 10^{6} Hz). Comparison of the experimental data with the theoretical calculations shows that the ion component of the plasma must be taken into account.

In the first part of this paper [1] the experimental set-up and the measurement technique were described, and the behavior of a plasma in an ac electric field but in the absence of a magnetic field was studied. /2029

It is well known that the high frequency properties of the plasma change in the presence of a sufficiently strong magnetic field. On this basis, we have investigated the plasma behavior in an ac electric field for the case when the plasma is also placed in a longitudinal magnetic field H up to 1200 oe, and whose direction is perpendicular to that of the electric field.

Just as in [1], the intensity $U_{pl}(r)$ at the output of the measuring circuit was measured in proportion to the intensity of the ac electric field in the plasma. These values $U_{pl}(r)$ were compared with the theoretical $U^{r}_{pl}(r) = \gamma U_{o}(r)$, where $U_{o}(r)$ is the intensity at the output of the measuring circuit in the absence of plasma and γ is the ratio of the intensity of the ac electric field in plasma to the intensity in vacuum.

In order to compute γ it is necessary to find the complex impedance of the plasma layer as established by the corresponding complex permitivity ε^{pl} and admittance σ_{pl}, which in a magnetized plasma are tensor values. In our case only the radial component of a magnetic field is present. Therefore, ε and σ are expressed by the tensor's diagonal component of the complex permitivity of the plasma.

$$\varepsilon'_{xx} = \varepsilon_{xx} - i\frac{4\pi\sigma_{xx}}{\omega} = \varepsilon_{nx} - i\frac{4\pi\sigma_{pl}}{\omega}.$$

* Numbers in the margin indicate pagination in the foreign text.

Using the expression for ε'_{xx} in [2], we write in a hydromagnetic approximation:

$$\varepsilon_{pl} = 1 - (\alpha_e + \alpha_i) N,$$
$$\alpha_e = \frac{4\pi e^2 (\omega^2 + \nu_e^2 - \omega_{Be}^2)}{m_e [(\omega^2 - \nu_e^2 - \omega_{Be}^2)^2 + 4\nu_e^2 \omega^2]}, \quad \alpha_i = \frac{4\pi e^2 (\omega^2 + \nu_i^2 - \omega_{Bi}^2)}{m_i [(\omega^2 - \nu_i^2 - \omega_{Bi}^2)^2 + 4\nu_i^2 \omega^2]},$$
$$\sigma_{pl} = (\beta_e + \beta_i) N, \tag{1}$$
$$\beta_e = \frac{e^2 \nu_e (\omega^2 + \nu_e^2 + \omega_{Be}^2)}{m_e \omega [(\omega^2 - \nu_e^2 - \omega_{Be}^2)^2 + 4\nu_e^2 \omega^2]}, \quad \beta_i = \frac{e^2 \nu_i (\omega^2 + \nu_i^2 + \omega_{Bi}^2)}{m_i \omega [(\omega^2 - \nu_i^2 - \omega_{Bi}^2)^2 + 4\nu_i^2 \omega^2]}.$$

where N is the plasma density, e is the electron charge, m_e and m_i are the /2030
masses of the electron and of the ion respectively, $W = 2\pi f$ is the operating frequency, W_{Be} and W_{Bi} are the electron and ion cyclotron frequencies, V_e and V_i are the effective collision frequencies of electrons and ions with gas atoms respectively.

In the presence of a magnetic field, the plasma is essentially heterogenerous in its cross section due to the contraction of the plasma cord. In the case when γ is computed, the heterogeneity of the plasma can be taken into account by dividing the plasma layer into a number (k) of layers, each of which is assumed to be uniform. The equivalent circuit diagram for this case is shown in Figure 1. In this case ε_i and σ_i are the permitivity and admittance of the i-th layer. Having computed the impedance of each layer and then the total impedance of the whole circuit, we obtain the following expression for $\gamma_i (k = 10)$:

$$\gamma_i = \frac{\left| \dfrac{\ln \frac{r_{i+1}}{r_i}}{\sigma_i \left(1 + \omega^2 \frac{\varepsilon_i^2}{\sigma_i^2}\right)} - i \dfrac{\omega \varepsilon_i \ln \frac{r_{i+1}}{r_i}}{\sigma_i^2 \left(1 + \omega^2 \frac{\varepsilon_i^2}{\sigma_i^2}\right)} \right| \left\{ \sum_{k=2}^{11} \dfrac{\ln \frac{r_{k+1}}{r_k}}{\varepsilon_2} + \dfrac{\ln \frac{r_2}{r_1} + \ln \frac{r_{13}}{r_{12}}}{\varepsilon_1} \right\}}{\left| \sum_{k=2}^{11} \dfrac{\ln \frac{r_{k+1}}{r_k}}{\sigma_k \left(1 + \omega^2 \frac{\varepsilon_k^2}{\sigma_k^2}\right)} - i \left(\sum_{k=2}^{11} \dfrac{\omega \varepsilon_k \ln \frac{r_{k+1}}{r_k}}{\sigma_k^2 \left(1 + \omega^2 \frac{\varepsilon_k^2}{\sigma_k^2}\right)} + \dfrac{\ln \frac{r_2}{r_1} + \ln \frac{r_{13}}{r_{12}}}{\omega \varepsilon_1} \right) \right| \dfrac{\ln \frac{r_{i+1}}{r_i}}{\varepsilon_2}} \tag{2}$$

where r_1 and r_2 are the inner and outer radii of the insulating layer near the core, while r_{12} and r_{13} are the inner and outer radii of the insulating layer near the wall.

The values of the plasma concentration N, necessary for the computation of γ, are found from probing measurements. Since in a magnetic field the usual probing methods are not applicable, the Boehm formula was used to express the density [3]:

$$j_{+} = 0.4\, N \sqrt{\frac{2kT_e}{m_i}}, \tag{3}$$

where j_+ is the ion saturation current, m_i is the ion mass, T_e is the electron temperature, k is the Boltzmann constant.

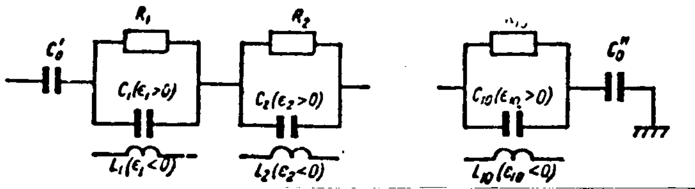

Figure 1

It is assumed that the values of the electron temperature entering into the formula are equal to those achieved under experimental conditions (discharge current, gas pressure) at H = 0.

The error generated by the inaccuracy of T_e is negligible since T_e enters into (3) to the 1/2 power.

Thus, if we know the distribution of the plasma density along the discharge radius, then it is possible to estimate γ at different distances from the axis, to find $U^r_{pl}(r)$ and to compare it with the experimental result $U_{pl}(r)$. /2031

Under our experimental conditions various possibilities can occur as follows from analysis of the correlations in (1), and their experimental verification is of interest. The behavior of the plasma in an ac electric field, which depends on the correlation between W, W_{Be}, V_e, and also W, W_{Bi}, V_i, can be interpreted from the reactive ε_{pl} and the active σ_{pl} components of the complex impedance of the plasma. It is characteristic that the ε_{pl} and σ_{pl} themselves can in various cases be expressed not only in terms of an electron component but also include the ion component of the plasma, and in some occasions the influence of the ion component predominates. The increase of the influence of the ion components is explained by the fact that in weak magnetic fields H ~ 100 oe. The correlations $H \ll W_{Be}$, $V_e \ll W_{Be}$ are already valid even for the maximum values of W and V_e under the conditions of our experiment. As a result, α_e and β_e are proportional to $1/H^2$ (See (1)).

The condition $W \ll W_{Bi}$ for the ions is satisfied only when $H > 10^4$e, therefore α_i and β_i are much less sensitive to changes in H than α_e and β_e.

Figure 2 shows the experimental $U_{pl}(r)$ (curves 1, 2) and calculated U^r_{pl} (curves 1', 2') plots of the intensity at the output of the measuring circuit as a function of the distance of the measuring dipole from the discharge chamber axis at various plasma densities N_o (N_o being the plasma density at the distance r = 1 cm).

Since here the conditions $\alpha_e \ll \alpha_i$ and $\beta_e \ll \beta_i$ are satisfied, the behavior of the plasma in an ac electric field is conditioned by the motion of the ions. It is sufficiently clear that the calculated and the experimental curves, essentially differ from their analogous curves for H = 0 as presented in [1], where H as a function of the distance from the axis behaved as 1/r approximately. Such a sharp change in the character of the function $U_{pl}(r)$ /2032
is explained by the reallocation of the ac intensity between plasma layers which is conditioned by the actual gradient of the plasma density along the radius (see Figure 3). In the case described, the reactive part of the plasma impedance is characterized by:

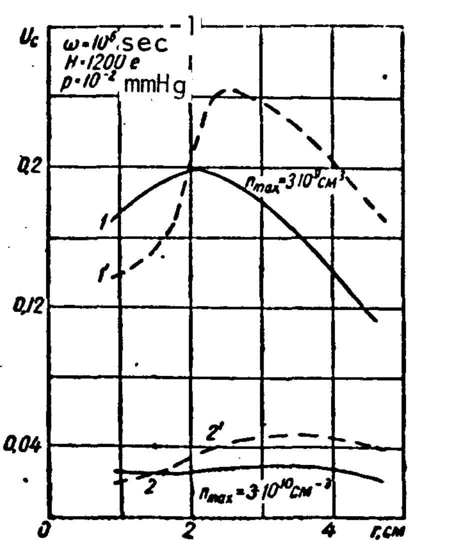

Figure 2

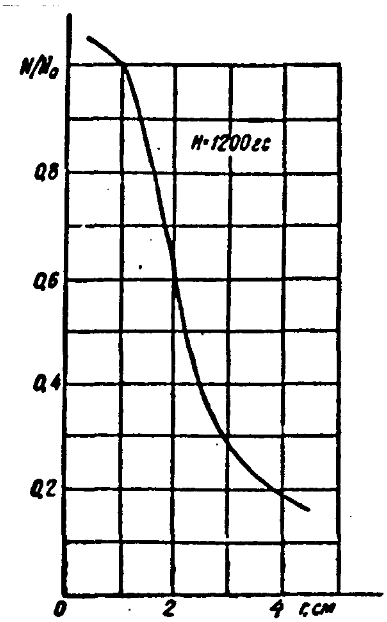

Figure 3

Figures 4 and 5 show the experimental (curves 1, 2, 3) and calculated (1', 2') functions $U_{pl}(r)$, $U^r_{pl}(r)$, for the condition when the plasma acts as an inductance. The characteristic difference between these two cases is that in the first case (Figure 4) the basic contribution to the complex impedance is governed by the active component ($\alpha_i \ll \beta_i$) while in the other case (Figure 5) the converse occurs ($\alpha_i \gg \beta_i$). As before, the contribution of the electron component to ε_{pl} and σ_{pl} can be ignored ($\alpha_e \ll \alpha_i$, $\beta_e \ll \beta_i$).

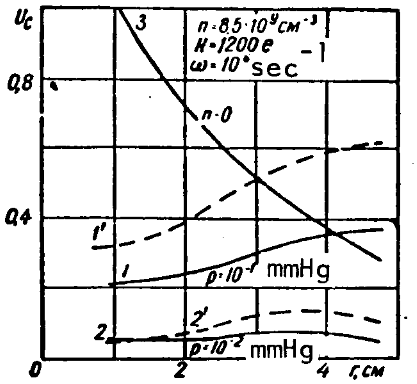

Figure 4

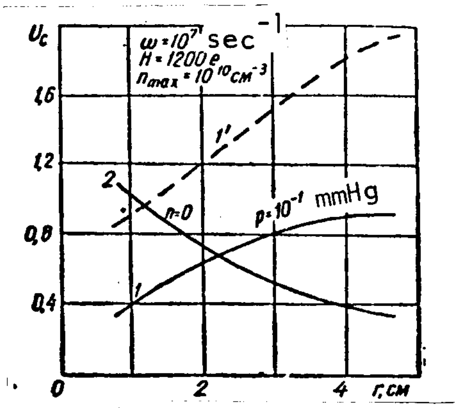

Figure 5

We see that in both cases the calculated functions $U^r_{pl}(r)$ correctly represent the shape of the experimental functions $U_{pl}(r)$, although in the second case (Figure 5) the calculated function is located much higher than the experimental one. This means that the complex impedance of the plasma is essentially less than can be concluded from the calculation.

A value of the calculated $U^r_{pl}(r)$ of the order of 1-1/2 to 3 times the experimental one was observed as a rule in all cases when the frequency was $W = 10^7 sec^{-1}$. At the frequency $W = 10^6 sec^{-1}$, the differences between the calculated and the experimental results do not in general exceed 30-50%, the calculated curves $U^r_{pl}(r)$ being located both above and below the experimental ones (see Figures 2, 4).

We note that the differences between the experimental and calculated functions at $W = 10^7 sec^{-1}$ cannot be explained by experimental errors say, errors in measurement of plasma density related to the use of the probing methods in the magnetic field. The calculations made for densities 5×10^9 and $2 \times 10^{10} cm^{-3}$ do not show better agreement with the experiment.

The reasons for the de[illegible]ase in the complex impedance of the plasma (when compared to the ca[illegible]s) at $w = 10^7 sec^{-1}$ has not been resolved yet.

It should be mentioned that no notable effects were observed experimentally in connection with the resonance in the circuit created by the plasma (inductance) and the insulating layers near the core and near the wall (capacitance).

When the plasma density is increased, i.e., a constant decrease in /2033
$U_{pl}(r)$ takes place although in accordance with the computation the values of $U^{r}_{pl}(r)$ must pass through a maximum.

It is true that in some cases (see Figure 4) the values of $U_{pl}(r)$ at r = 2-3 cm exceed the value of $U_{o}(r)$, i.e., the intensity of the field in plasma is higher than when plasma is absent however, it is necessary to take into account that such an excess of $U_{pl}(r)$ over $U_{o}(r)$ can be attributed to a large extent to the reallocation of the ac field caused by the heterogeneity of the plasma along the radius.

The aforesaid experimental results on the whole confirm the feasibility of the hydromagnetic approximation for a description of the behavior of plasma in an ac electric field both in the presence and in the absence of a magnetic field.

These results also indicate the necessity of taking into account the influence of the ion component when the high frequency properties of plasma in a magnetic field are considered.

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